Deterministic Entanglement of Trapped-Ion Spin-Qubits

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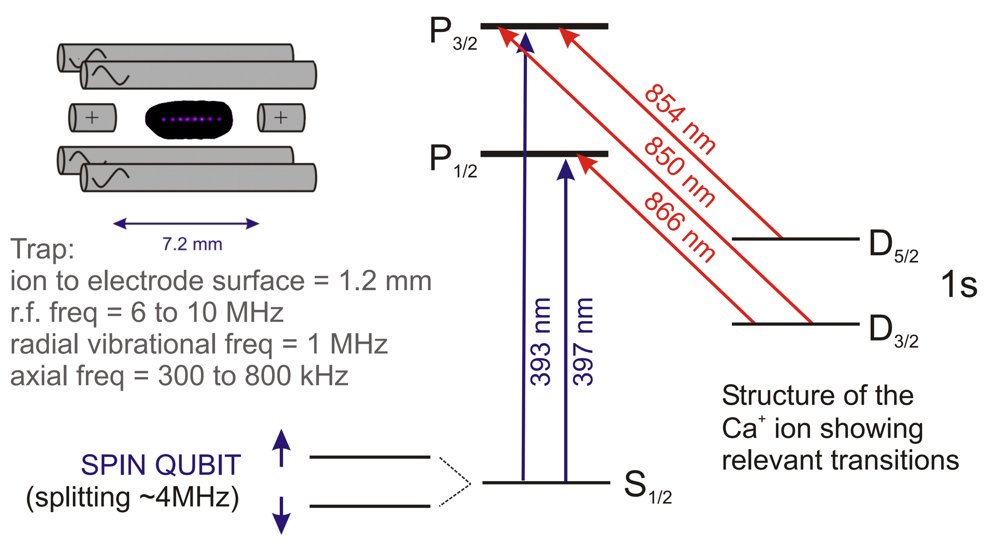
Main points

We present experiments and theory in quantum information processing using trapped ions.
This poster concentrates on entanglement and gates: see accompanying poster for cooling, coherence.

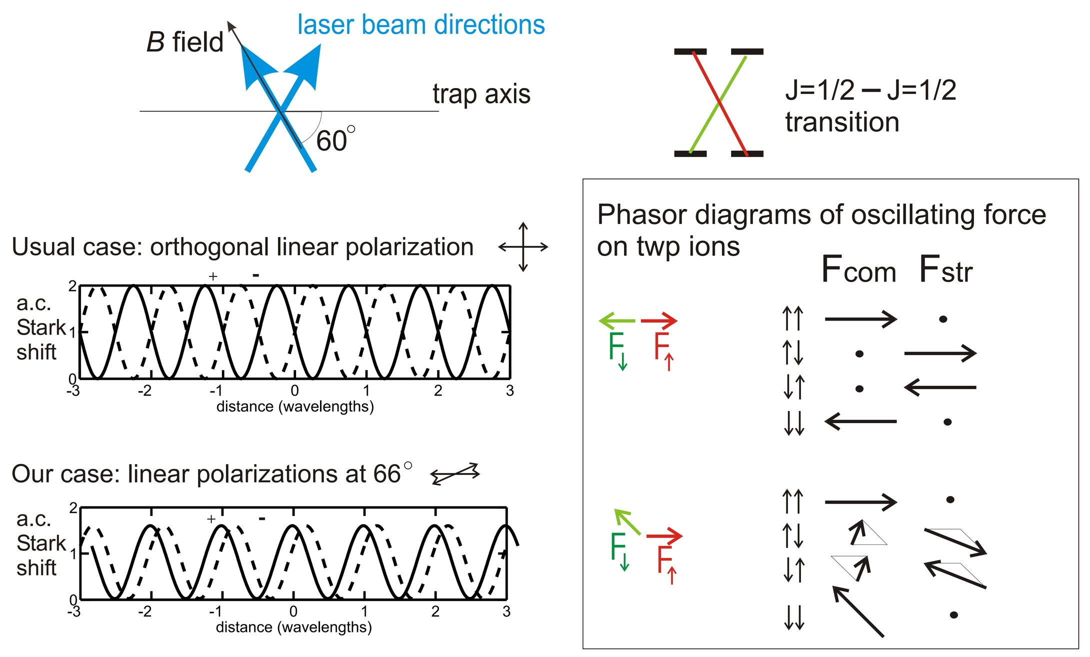


Summary of Results

- 10 two-ion (2 qubit) Rabi flops with high visibility
- Deterministic entanglement of 2 ions (calcium 40 spin qubits) at 82(2)% fidelity
- Schrodinger cat with 1 ion and motion:
  up to (<n>=12)
  well outside Lamb-Dicke regime: $^2 2n$ =
  = 1 preserved for 422 s with 80(20)% fidelity
  also = -2,0,+2 with 2 ions
- robust convenient tomography method
- (th.) factorization of general phase gates (ask for details)
- (th.) composite pulses for fast gate (t=1/trap freq) insensitive to optical phase

Spin-dependent force

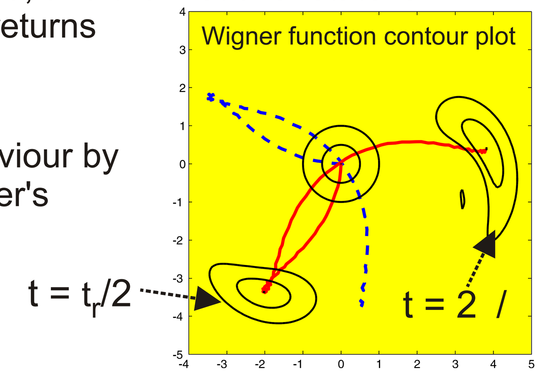
For two-qubit gates we use spin-dependent forces: push ions depending on spin state
Coulomb interaction gives a two-qubit phase.
The force is an optical dipole force in a standing wave with polarization gradient.



Difference frequency of laser beams oscillating force on ion

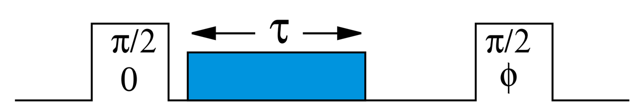
- A classical force displaces the motional state in phase space.
- In Lamb-Dicke regime, extent of motional wavepacket << the force appears to be spatially uniform, and an oscillating force drives the motional state around a circular loop in phase space. It returns to the origin after t = 2 / , where =
- Outside the Lamb-Dicke regime, the trajectory of the motional state through phase space is modified, and the motional state is squeezed. The motional state returns to the origin early, ie. t_r < 2 / .

We simulate the NLD regime behaviour by numerical integration of Schrodinger's equation.



Schrödinger Cat experiments

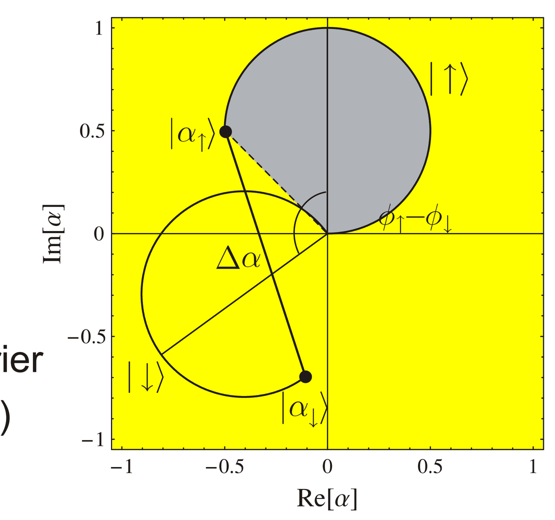
Coherent states of a harmonic oscillator approximate to classical motion, and a superposition of such states at mesoscopic excitation <n> is a type of Schrödinger cat.
Oscillating spin-dependent force create such mesoscopic superpositions with single or pairs of ions. Spin state = measuring device entangled with the motion. We prove the 'cat' maintains its coherence by bringing the two parts back together and observing an interference. [As first demonstrated by Monroe *et al.* Science 272 1131



Observe P( ) as a function of .

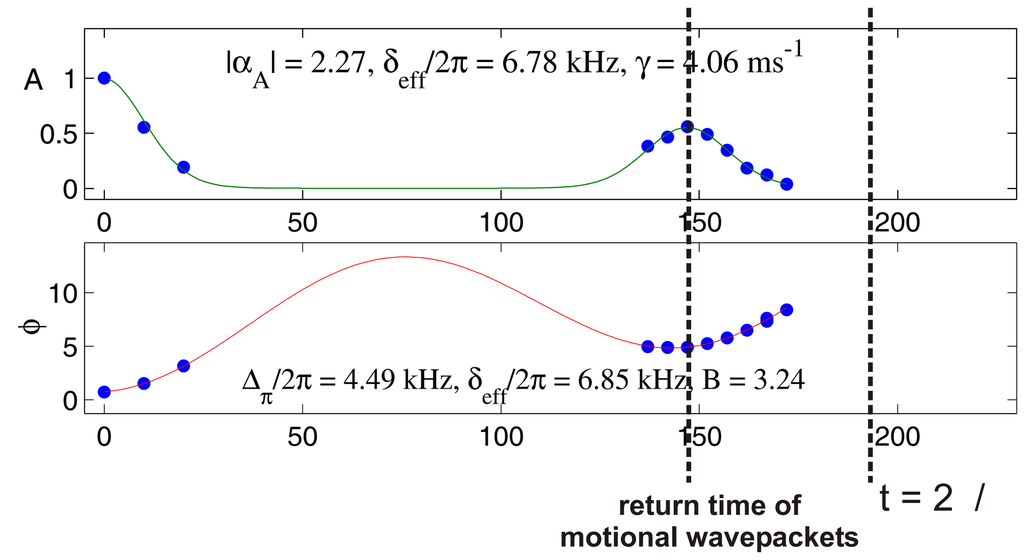
$$P(\uparrow)=\frac{1}{2}\left(1-\mathrm{Re}\left[\langle\alpha_\uparrow|\alpha_\downarrow\rangle e^{i(\phi-\Delta_\pi\tau)}\right]\right)$$

where is a light shift due to off-resonant carrier excitation (due to component of the light field)



Fringe amplitude
$A=|\langle\alpha_\uparrow|\alpha_\downarrow\rangle|$

Fringe phase
$\mathrm{Arg}(\langle\alpha_\uparrow|\alpha_\downarrow\rangle)+\Delta_\pi\tau$



We observe cat states with = 5.4, $_{max}$ = 4, and a motional coherence time T_2 = 170 s.

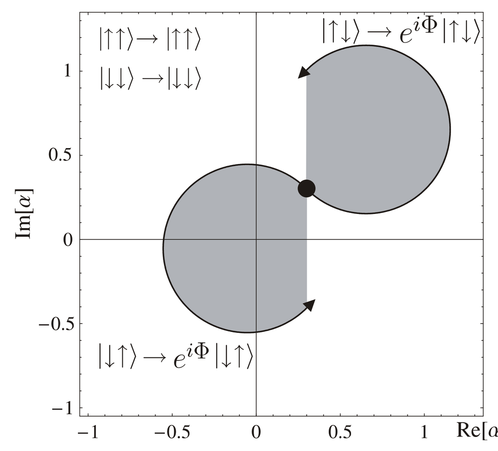
Deterministic entanglement

- Deterministic (i.e. single-shot, no post-selection) entanglement of 2 spin-qubits
- gate uses oscillating spin-dependent driving force used to create Schrödinger cats, with force frequency close to $_{str}$ & ion separation = integer number of standing wave periods

=> only stretch mode excited
=> states acquire a phase; do not.

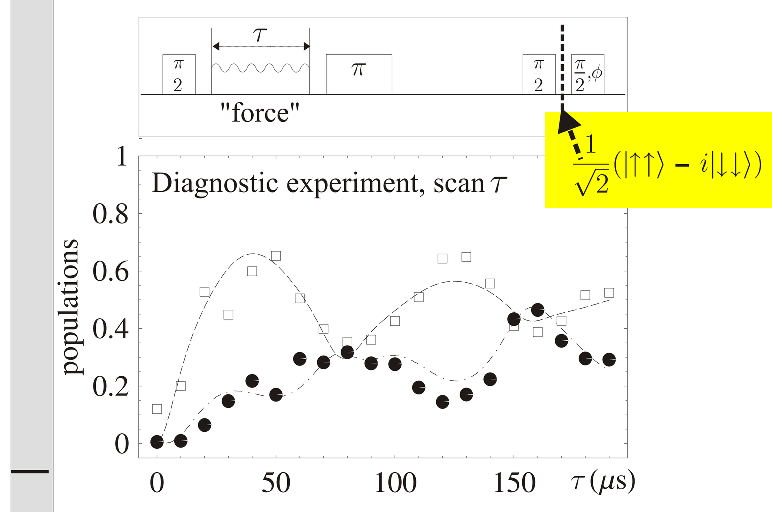
- Gate operation

$$\hat{U}=\begin{pmatrix}1&&&\\&i&&\\&&i&\\&&&1\end{pmatrix}$$

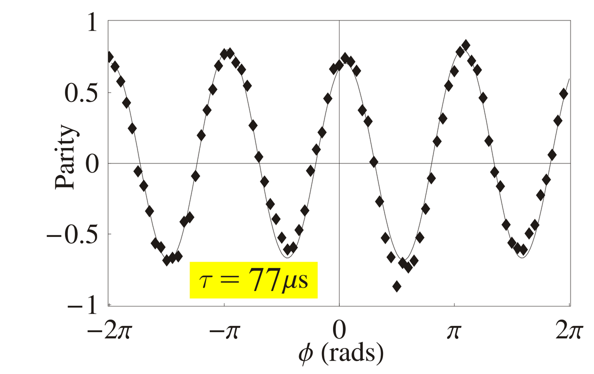


(Leibfried *et al.* [Nature 422 412 (2003)].)

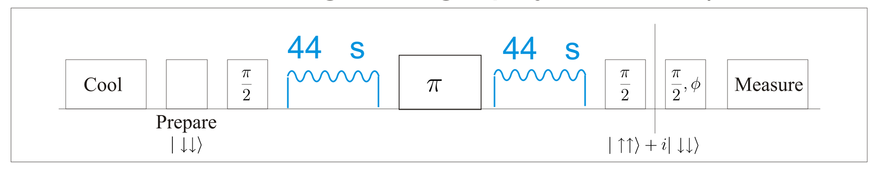
Experiments: $_{com}$ = 500 kHz, ion sep = 9 mm = 22
Single pulse method: Implements gate + single qubit rotations (due to light shift).
For = 2 and = 1/ , we get the entangled state.



A further /2 analysis pulse with variable phase demonstrates cos(2) oscillations in the parity signal with amplitude >0.5.
Entangled state fidelity > 75(5)%



Two pulse method: One pulse in each half of spin-echo. Single qubit rotations cancel. Entangled state density matrix reconstructed using tomography method (see below).
Fidelity 82(2)%

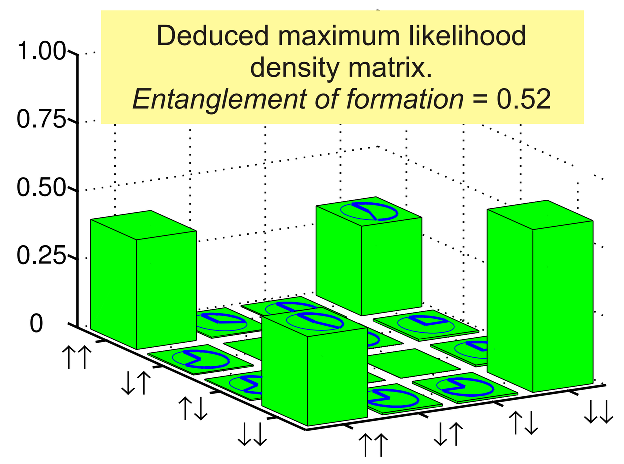


Tomography

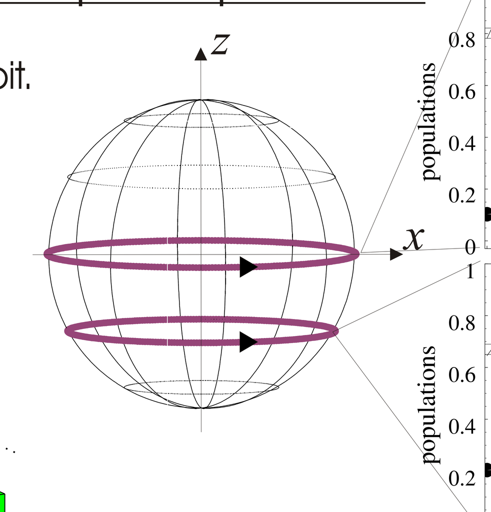
In general, tomography involves accumulating information by applying well-chosen rotations to the qubits and measuring them in a fixed basis. We developed a convenient scheme which is robust against typical experimental issues.
The rotation is through about an axis in the x-y plane. is scanned from - to
P(spin state) = sinusoidal functions of this allows robust curve-fitting of sin functions with period and 2 and an offset Each contribution to the fit yields 1 or 2 real numbers; two values of are needed for complete information. A maximum likelihood estimation method is then used to obtain the physical density matrix closest to that obtained from the data.

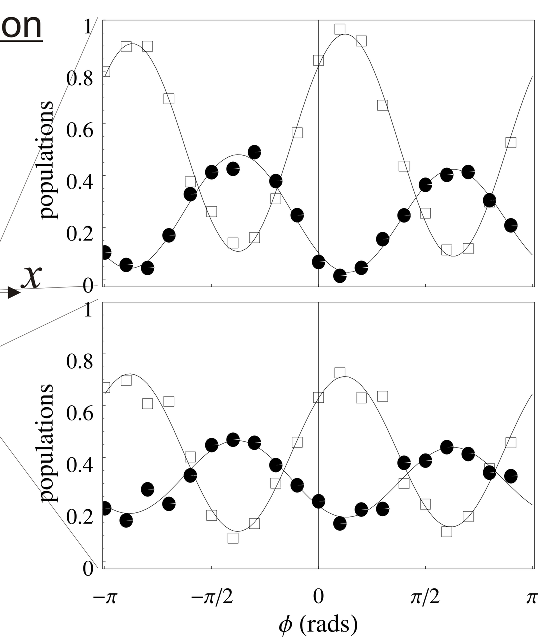
Experimental realisation:
equal rotations applied to each qubit.

Results shown are for experiments performed on an entangled state.



Bloch Sphere representation





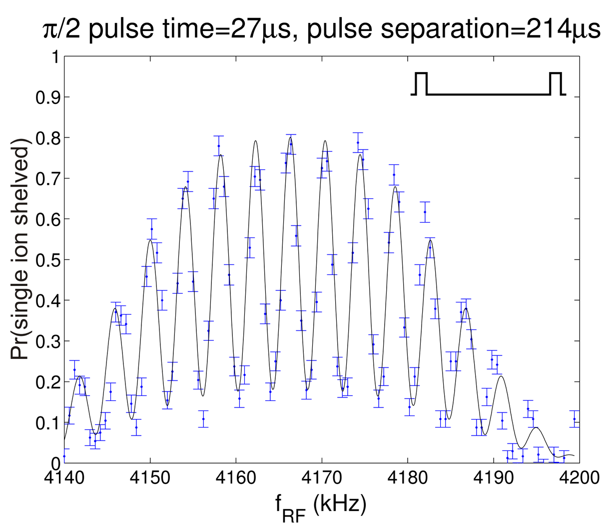
(Our measurement method does not distinguish from but this has little influence for this example

Single-qubit gates, 1-2 ions

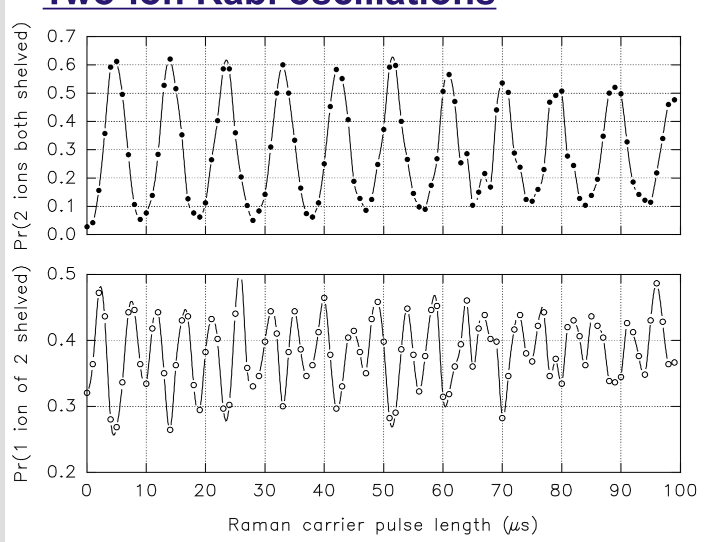
Spin qubit state coherently manipulated either by magnetic resonance or by stimulated Raman transition.

Single-ion Ramsey fringes

This data is for a two-pulse Ramsey sequence using magnetic resonance with a single trapped ion. Interference fringes are seen as the RF frequency is scanned.



Two-ion Rabi oscillations



2-ion spin-state = 2 qubits. Rabi flopping, here driven by the Raman transition (4.5 s time), gives a single-qubit rotation applied to both qubits simultaneously.

EIT readout 0,1 or 2 ions shelved
infer P(P(P(P(

Composite pulses for fast robust gates

Wobble gate works well at low $_{str}$ but is slow,
At high both COM and STR modes excited, can't close both loops in a single pulse (incommensurate freq).
Tailor f(t) in order to go faster? : lose insensitivity to optical phase $_0$.

- We find fast composite pulse sequences maintaining insensitivity to $_0$
- Issues: loop closure, constant area, lightshift phase

$$f(t)=\sum_{n=1}^{N}T((t-t_n)/\tau_n)\,f_n\sin(\omega_n t+\phi_n).$$

top hat

$$\phi_n=\phi_0+\Delta\phi_n$$

random fixed

$$\alpha(t)-\alpha(0)=\frac{i}{m\omega_0 a}\int_0^t e^{i\omega_0 t}f(t)dt.$$